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FLEXSTAB

A Summary of the Functions and Capabilities of the NASA Flexible Airplane Analysis Computer System

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16. Abstract

This report provides a brief description of NASA's aeroelastic stability and control computer program—FLEXSTAB. Information is provided to aid potential users in evaluating possible use of FLEXSTAB. A summary of the program's capabilities, the scope and limitations of its formulation, and a description of its documentation is provided. Computer program hardware and software requirements and recent user experience are also discussed.

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1.0 INTRODUCTION

The purpose of this report is to give a brief description of the FLEXSTAB computer program system. This is to provide insight as to the suitability of FLEXSTAB for working problems of interest. A glossary has been included as an aid in defining certain terms in this report. For additional information, the documents listed in section 6.0 (refs. 1 through 4) should be consulted.

The FLEXSTAB system of digital computer programs uses linear theories to evaluate static and dynamic stability, trim state, inertial and aerodynamic loading, and elastic deformations of aircraft configurations at supersonic and subsonic speeds. The distinctive features of the FLEXSTAB system are:

● It is based on unified linear aerodynamic, structural, and dynamic analytical methods valid for a wide variety of aircraft configurations.

● It has the capability for incorporating empirical and theoretical corrections in aerodynamic and stability analysis.

● It merges the low-frequency dynamics of a flexible body with low-frequency unsteady aerodynamics for aircraft dynamic stability analysis.

The FLEXSTAB system is suitable for solving a wide variety of problems; primary emphasis has been placed on analyzing the stability and control characteristics of flexible aircraft. As a consequence, the unsteady formulation is restricted to low-frequency analysis. Reduced frequencies, k, should be much less than 1, for $k \ll 1$: the formulation error is of the order k^2. The system is also capable of solving simple rigid aerodynamic problems in a convenient and efficient manner. By-products of these analyses include the calculation of aerodynamic load distributions, and for elastic solutions, the calculation of net loads (aerodynamic plus inertial) at the structure nodes (grid points), and structural deformations. As in all aerodynamic potential flow programs, the flow is considered to be inviscid: that is, viscous flow effects are neglected. Details of the capability of the system and its limitations are discussed in sections 2.0 and 3.0.

The FLEXSTAB system is composed of a group of 14 individual computer programs (table 1) that can be linked by tape or disk data transfer. These programs can be executed singly or linked for consecutive execution in a single run. The system is designed to operate on CDC 6000-series computers with 131 k_8 word central memory and CDC 7000-series computers. An IBM 360/370-0S version is also being developed. Plotting capability on CalComp plotters is also available. Additional equipment requirements are discussed in section 5.0.

TABLE 1.–FLEXSTAB SYSTEM

GEOMETRY DEFINITION

    Geometry Definition Program

AERODYNAMIC MODELING

    Aerodynamic Influence Coefficient Program
    AIC Matrix Correction Program

STRUCTURAL MODELING

    Internal Structural Influence Coefficient Program
    Elastic Axis Plot Program
    Normal Modes Program
    Normal Modes Plot Program
    External Structural Influence Coefficient Program

PROBLEM ANALYSIS

    Stability Derivatives and Static Stability Program
    Pressure Distribution Plot Program
    Time Histories Program
    Time Histories Plot Program
    Aerodynamic Loads Program
    Structural Loads Program

FLEXSTAB is essentially an open-ended program in that the number of aerodynamic segments and structural degrees of freedom used to describe an aircraft configuration are generally limited by economic considerations rather than size limitations of the FLEXSTAB system. Computational procedures have been developed to provide efficiency for both large and small problems. Dual code is provided in the matrix operation subroutines for efficient in-core or out-of-core calculations. Assembly language code has been written into subroutines where speed is essential, such as the matrix vector inner product computations, for example.

FLEXSTAB is a user-oriented system. Structural and geometric data are only defined once and thereafter are transferred between programs by magnetic tape or disk. Several options are available to allow the user to tailor the program analysis to his particular problem. The user is given a choice of using either English or metric units of measure in the definition and analysis of a configuration. The printed output is liberally annotated and logically organized. Selected results are also available as plotted output. The structure (sec. 4.0) of the FLEXSTAB system allows the user to analyze a problem in stages, checking each step as he goes, or to link individual programs together through job control cards and do a complete analysis in a single run.

Section 7.0 discusses the current user experience of the system. A system the size of FLEXSTAB can never be completely debugged. However, much of the system has been used in varying degrees, and all major features of the system are considered to be free of error. The purpose of this section is to convey some indication of the measure of reliability of both the program logic and the theoretical formulation. Section 8.0 briefly describes the version control procedure for FLEXSTAB.

2.0 SUMMARY OF PROGRAM ANALYSIS CAPABILITY

A wide range of analysis capability has been incorporated into the FLEXSTAB system, as indicated in table 2. Configurations to be analyzed may be made up of multiple wings, bodies, tails, nacelles, etc., where structures are represented as being rigid, static-elastic, or residual-elastic, in which the dynamic stability analysis uses the free vibration mode shape amplitudes as structural degrees of freedom. A typical analysis sequence is shown in figure 1. Data describing the geometric and structural characteristics and the specific flight condition to be analyzed are input. The pertinent geometric data and aerodynamic and structural matrices are calculated and then used to calculate the aerodynamic and stability characteristics and structural loads of the aircraft. A discussion of the scope and limitations of the FLEXSTAB formulation will follow in section 3.0.

2.1 AIRCRAFT STABILITY AND CONTROL

The FLEXSTAB system analyzes stability and control characteristics of flexible or rigid aircraft. The analysis is performed at prescribed flight conditions defined by Mach number, altitude, angle of bank, pitch, yaw, and roll rates, and either flightpath angle or thrust. The system balances the aircraft for trimmed flight and computes the values of the trim variables (that is, the trim angles of attack and sideslip, elevator, aileron, and rudder control settings, and either flightpath angle or thrust). Empirical aerodynamic data can be included in the calculation of resulting trim condition. An alternate method allows the user to specify to the trim parameters. This option is useful for specifying untrimmed flight maneuvers, for calculating loads for unit control deflections, or for matching rigid wind tunnel test conditions. Rigidly supported flexible wind tunnel models cannot be analyzed.

The FLEXSTAB system will calculate:

- Static stability and control derivatives listed in table 3

- Static stability parameters such as static and maneuver margins, elevator control effectiveness, and speed/stick stability, listed in table 4

- Dynamic stability and control derivatives listed in table 5

All of these stability and control parameters follow standard conventions, as defined in references 1 and 5. The system also computes the roots of linear perturbation equations of motion based on the stability derivatives either calculated internally by the system or input as empirical data by the user. These roots provide the user with the response frequencies used to evaluate the stability and control acceptability of a configuration (i.e., short period, phugoid, etc.). This output is obtained from a characteristic rooting analysis and is listed in table 6.

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2.2 TIME HISTORIES

If the perturbation equations of motion are nonlinear (as a consequence of the user supplying nonlinear aerodynamic data or wanting to investigate large perturbation motions), or if discrete gust disturbances are input, dynamic stability characteristics are evaluated from the time histories plots.

TABLE 2.—FLEXSTAB CAPABILITY SUMMARY

Scope and limitations of the FLEXSTAB system	Types of problems solved	Output quantities generated FLEXSTAB programs

Configuration
  • Multiple wings and bodies (i.e., wing-body-tail-nacelles-struts, etc.)
  • Must be symmetric about X-Z plane
Structure
  • Rigid
  • Flexible—linear
    • Beam theory
    • Interface with finite element structures programs outside FLEXSTAB SYSTEM
	Aircraft stability and control	• Tabulated
		  • Static stability derivatives table 3
		  • Static stability and trim parameters table 4
		  • Dynamic stability derivatives table 5
		  • Characteristic roots table 6

Aerodynamics
  • Supersonic
  • Subsonic
  • Potential flow
    • Linear
	Time histories
	  • Discrete gust response
		• Tabulated, plotted, and tape
		  • Motion variables table 7

• Nonviscous
    • No separation
    • Small angles
  • Steady
  • Unsteady
    • Low frequency $\omega \ell / U_1$
    • No flutter capability
    • Interference effects
	Lifting pressure distribution	• Tabulated, plotted, and tape
		  • Steady
		  • Unsteady (low-frequency, thin bodies only)
		  • Airloads at aerodynamic panels

Stability analysis
  • Longitudinal
  • Lateral directional
    • No angle of attack/ sideslip coupling
  • Steady analysis
    • Rigid
    • Static elastic
  • Dynamic analysis
    • Rigid
    • Static elastic
    • Residual elastic
    • Controls—fixed
	Structural loads and deflections (Due to aerodynamic and inertial forces)	• Tabulated and tape
		  • Static airloads and inertial loads at structural nodes
		  • Static elastic deflections at aerodynamic panels and structural nodes
		  • Perturbation loads on elastic axis that are functions of:
		    • Motion variables
		    • Control surface deflections

Empirical inputs
  • Supplement or replace program calculated derivatives
	Jig and design point shape	• Tabulated, tape, and cards
		  • Ordinates and slopes at aerodynamic centroids

	Configuration change	• Any of the above

• Modify aerodynamic influence coefficient matrix
  • Modify boundary conditions
  • Modify pressure loading
	Extended FLEXSTAB capabilities	• Any of the above interfaced with computer programs outside the FLEXSTAB system, e.g., FLEXSTAB-NASTRAN

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C_{L_o}	lift	coefficient at	$\alpha = \delta_e = 0$
C_{D_o}	drag	coefficient at	$\alpha = \delta_e = 0$
C_{m_o}	pitching moment	coefficient at	$\alpha = \delta_e = 0$
C_{L_α}	lift	coefficient due to angle of attack	$\partial C_L/\partial \alpha$
C_{D_α}	drag	coefficient due to angle of attack	$\partial C_D/\partial \alpha$
C_{m_α}	pitching moment	coefficient due to angle of attack	$\partial C_m/\partial \alpha$
$C_{L_{\hat{q}}}$	lift	coefficient due to pitch rate	$\partial C_L/\partial(q\bar{c}/2u_1)$
$C_{D_{\hat{q}}}$	drag	coefficient due to pitch rate	$\partial C_D/\partial(q\bar{c}/2u_1)$
$C_{m_{\hat{q}}}$	pitching moment	coefficient due to pitch rate	$\partial C_m/\partial(q\bar{c}/2u_1)$
$C_{L_{\delta_e}}$	lift	coefficient due to elevator deflection	$\partial C_L/\partial \delta_e$
$C_{D_{\delta_e}}$	drag	coefficient due to elevator deflection	$\partial C_D/\partial \delta_e$
$C_{m_{\delta_e}}$	pitching moment	coefficient due to elevator deflection	$\partial C_m/\partial \delta_e$
$C_{y_{\hat{p}}}$	sideforce	coefficient due to roll rate	$\partial C_y/\partial(pb/2u_1)$
$C_{\ell_{\hat{p}}}$	rolling moment	coefficient due to roll rate	$\partial C_\ell/\partial(pb/2u_1)$
$C_{n_{\hat{p}}}$	yawing moment	coefficient due to roll rate	$\partial C_n/\partial(pb/2u_1)$
$C_{y_{\hat{r}}}$	sideforce	coefficient due to yaw rate	$\partial C_y/\partial(rb/2u_1)$
$C_{\ell_{\hat{r}}}$	rolling moment	coefficient due to yaw rate	$\partial C_\ell/\partial(rb/2u_1)$
$C_{n_{\hat{r}}}$	yawing moment	coefficient due to yaw rate	$\partial C_n/\partial(rb/2u_1)$
C_{y_β}	sideforce	coefficient due to sideslip	$\partial C_y/\partial \beta$
C_{ℓ_β}	rolling moment	coefficient due to sideslip	$\partial C_\ell/\partial \beta$
C_{n_β}	yawing moment	coefficient due to sideslip	$\partial C_n/\partial \beta$

[a]Printout from the Stability Derivatives and Static Stability Program

TABLE 3.—CONCLUDED

$C_{y_{\delta_a}}$	sideforce	coefficient due to aileron deflection (antisymmetrically deflected)	$\partial C_y / \partial \delta_a$
$C_{\ell_{\delta_a}}$	rolling moment	coefficient due to aileron deflection (antisymmetrically deflected)	$\partial C_\ell / \partial \delta_a$
$C_{n_{\delta_a}}$	yawing moment	coefficient due to aileron deflection (antisymmetrically deflected)	$\partial C_n / \partial \delta_a$
$C_{y_{\delta_r}}$	sideforce	coefficient due to rudder deflection	$\partial C_y / \partial \delta_r$
$C_{\ell_{\delta_r}}$	rolling moment	coefficient due to rudder deflection	$\partial C_\ell / \partial \delta_r$
$C_{n_{\delta_r}}$	yawing moment	coefficient due to rudder deflection	$\partial C_n / \partial \delta_r$

TABLE 4.—STATIC STABILITY AND TRIM PARAMETERS[a]

Trim Parameters	
α	angle of attack
β	angle of sideslip
δ_e	elevator deflection angle
δ_a	aileron deflection angle
δ_r	rudder deflection angle
T	thrust
γ	flight path angle
Trimmed Force Coefficients	
C_L	lift coefficient
C_D	drag coefficient
C_m	pitching moment coefficient
C_y	sideforce coefficient
C_ℓ	rolling moment coefficient
C_n	yawing moment coefficient
Static Stability Parameters	
$h_n - h$	static margin
h_n	neutral point
$h_m - h$	maneuver margin
$\partial \delta_e / \partial n$, $\dfrac{\Delta \delta_e}{n-1}$	elevator angle per g (turn, pullup)
$\partial \delta_e / \partial V$	speed stick stability

[a]Printout from the Stability Derivatives and Static Stability Program

TABLE 5.—DYNAMIC STABILITY DERIVATIVES AND CONTROL EFFECTIVENESS COEFFICIENTS[a]

$C_{L_{\dot{\alpha}}}$	lift	coefficient due to angle-of-attack rate	$\partial C_L / \partial (\dot{\alpha}\bar{c}/2u_1)$
$C_{D_{\dot{\alpha}}}$	drag	coefficient due to angle-of-attack rate	$\partial C_D / \partial (\dot{\alpha}\bar{c}/2u_1)$
$C_{m_{\dot{\alpha}}}$	pitching moment	coefficient due to angle-of-attack rate	$\partial C_m / \partial (\dot{\alpha}\bar{c}/2u_1)$
C_{L_u}	lift	coefficient due to speed change	$\partial C_L / \partial (u/u_1)$
C_{D_u}	drag	coefficient due to speed change	$\partial C_D / \partial (u/u_1)$
C_{m_u}	pitching moment	coefficient due to speed change	$\partial C_m / \partial (u/u_1)$
$C_{L_{\hat{q}}}$	lift	coefficient due to pitch acceleration	$\partial C_L / \partial (\dot{q}\bar{c}/4u_1^2)$
$C_{D_{\hat{q}}}$	drag	coefficient due to pitch acceleration	$\partial C_D / \partial (\dot{q}\bar{c}/4u_1^2)$
$C_{m_{\hat{q}}}$	pitching moment	coefficient due to pitch acceleration	$\partial C_m / \partial (\dot{q}\bar{c}/4u_1^2)$
$C_{y_{\hat{p}}}$	sideforce	coefficient due to roll acceleration	$\partial C_y / \partial (\dot{p}b^2/4u_1^2)$
$C_{\ell_{\hat{p}}}$	rolling moment	coefficient due to roll acceleration	$\partial C_\ell / \partial (\dot{p}b^2/4u_1^2)$
$C_{n_{\hat{p}}}$	yawing moment	coefficient due to roll acceleration	$\partial C_n / \partial (\dot{p}b^2/4u_1^2)$
$C_{y_{\hat{r}}}$	sideforce	coefficient due to yaw acceleration	$\partial C_y / \partial (\dot{r}b^2/4u_1^2)$
$C_{\ell_{\hat{r}}}$	rolling moment	coefficient due to yaw acceleration	$\partial C_\ell / \partial (\dot{r}b^2/4u_1^2)$
$C_{n_{\hat{r}}}$	yawing moment	coefficient due to yaw acceleration	$\partial C_n / \partial (\dot{r}b^2/4u_1^2)$
$C_{y_{\dot{\beta}}}$	sideforce	coefficient due to sideslip rate	$\partial C_y / \partial (\dot{\beta}b/2u_1)$
$C_{\ell_{\dot{\beta}}}$	rolling moment	coefficient due to sideslip rate	$\partial C_\ell / \partial (\dot{\beta}b/2u_1)$
$C_{n_{\dot{\beta}}}$	yawing moment	coefficient due to sideslip rate	$\partial C_n / \partial (\dot{\beta}b/2u_1)$

[a]From the Stability Derivatives and Static Stability Program

TABLE 5.—CONCLUDED

$C_{L_{\dot{\delta}_e}}$	lift	coefficient due to elevator deflection rate	$\partial C_L / \partial (\dot{\delta}_e \bar{c}/2u_1)$
$C_{D_{\dot{\delta}_e}}$	drag	coefficient due to elevator deflection rate	$\partial C_D / \partial (\dot{\delta}_e \bar{c}/2u_1)$
$C_{m_{\dot{\delta}_e}}$	pitching moment	coefficient due to elevator deflection rate	$\partial C_m / \partial (\dot{\delta}_e \bar{c}/2u_1)$
$C_{y_{\dot{\delta}_a}}$	sideforce	coefficient due to aileron deflection rate (antisymmetric deflection)	$\partial C_y / \partial (\dot{\delta}_a b/2u_1)$
$C_{\ell_{\dot{\delta}_a}}$	rolling moment	coefficient due to aileron deflection rate (antisymmetric deflection)	$\partial C_\ell / \partial (\dot{\delta}_a b/2u_1)$
$C_{n_{\dot{\delta}_a}}$	yawing moment	coefficient due to aileron deflection rate (antisymmetric deflection)	$\partial C_n / \partial (\dot{\delta}_a b/2u_1)$
$C_{y_{\dot{\delta}_r}}$	sideforce	coefficient due to rudder deflection rate	$\partial C_y / \partial (\dot{\delta}_r b/2u_1)$
$C_{\ell_{\dot{\delta}_r}}$	rolling moment	coefficient due to rudder deflection rate	$\partial C_\ell / \partial (\dot{\delta}_r b/2u_1)$
$C_{n_{\dot{\delta}_r}}$	yawing moment	coefficient due to rudder deflection rate	$\partial C_n / \partial (\dot{\delta}_r b/2u_1)$

TABLE 6.—CHARACTERISTIC EQUATION ROOTING[a]

Each real root and each oscillatory pair of roots are described individually.

For each eigenvalue the following is printed:

- Times and number of cycles to one-half (or double) and one-tenth amplitude
- Frequency and periods of modes
- Logarithmic decrement and ratio of successive maximum displacement
- Undamped natural frequencies of modes
- Damping ratio of modes
- Phase and amplitudes of modal coupling terms

[a]From the Stability Derivatives and Static Stability Program

Perturbations can be the result of the discrete gust velocity distribution, or they can be selected to be a sine wave, a one-minus-cosine wave, or a modified square wave with a reduced frequency much less than one, or they can be the result of initial position and/or velocity perturbations. The dynamic stability derivative data can be modified by user input tabular empirical data. The maximum permissible Euler angles of the resulting motion may also be specified.

The FLEXSTAB system computes the time histories of the aircraft's position and velocity with respect to both a local and an inertial reference system. Output can be both tabulated and plotted. A list of the specific parameters calculated is given in table 7.

2.3 LIFTING PRESSURE DISTRIBUTIONS

Lifting pressure distributions on the aircraft can be calculated in the course of the solution of any stability analysis problem. The effects on lifting pressure of any trim variable, aircraft flexibility, and low-frequency unsteady motion may be evaluated. The steady lifting pressures may be integrated to yield shear, bending, and torsion due to airloads on the aircraft. Program output is tabulated and may also be plotted or put on magnetic tape for other uses outside the FLEXSTAB system.

2.4 STRUCTURAL LOADS AND DEFLECTIONS

Loads, deflections, and rotations are calculated at aerodynamic panel centroids in the execution of any stability analysis problem. For residual elastic analysis, generalized aerodynamic modal forces are also calculated. Additional analysis capabilities depend on the form of the structural model input. For structural models defined within the FLEXSTAB system, static and dynamic elastic axis load matrices may be computed. Perturbation load matrices may be a function of motion variables, control surface deflections and modal variables for both symmetric and antisymmetric flight. For a structural model generated external to the FLEXSTAB system, elastic deflections due to steady net loads (aerodynamic plus inertial) and inertial loads can be calculated at the structural grid points for symmetric flight. Output is in tabulated form and may also be put on magnetic tape for use outside the FLEXSTAB system.

2.5 JIG OR DESIGN POINT SHAPE

The FLEXSTAB system can be used to calculate either the jig shape or design point shape of an elastic aircraft. The jig shape is defined as the shape of the airplane when it is completely unloaded, as when supported by jigs in the factory. The design point shape is the shape to which the elastic aircraft deforms at its design point flight conditions. Either shape may be used as input into the program, although the design point shape has meaning only at design point flight conditions. The camber shape, slopes, and displacements of either the jig shape or design point shape can be output as tabulated, punched card, or magnetic tape data.

TABLE 7.—TIME HISTORIES[a]

X'_{OP}	cg position perturbation
Y'_{OP}	cg position perturbation
Z'_{OP}	cg position perturbation
$\dot{X}'_{OP}$	cg position perturbation velocity
$\dot{Y}'_{OP}$	cg position perturbation velocity
$\dot{Z}'_{OP}$	cg position perturbation velocity
θ	Body Axis angular orientation (Euler angles)
ϕ	Body Axis angular orientation (Euler angles)
ψ	Body Axis angular orientation (Euler angles)
V_c	total velocity
V_{cp}	total perturbation
N_p	perturbation load factor at cg
α_p	perturbation angle of attack
β_p	perturbation sideslip angle
θ_p	perturbation angular orientation
ϕ_p	perturbation angular orientation
ψ_p	perturbation angular orientation
$\dot{\theta}_p$	perturbation angular rate
$\dot{\phi}_p$	perturbation angular rate
$\dot{\psi}_p$	perturbation angular rate
u	perturbation linear velocity
v	perturbation linear velocity
w	perturbation linear velocity
p	perturbation angular velocity
q	perturbation angular velocity
r	perturbation angular velocity
$\dot{u}$	perturbation linear acceleration
$\dot{v}$	perturbation linear acceleration
$\dot{w}$	perturbation linear acceleration
$\dot{p}$	perturbation angular acceleration
$\dot{q}$	perturbation angular acceleration
$\dot{r}$	perturbation angular acceleration

Note: 1. X', Y', Z' are the coordinates in the Inertial Axis System.

2. u, v, w, and p, q, r are perturbation velocities in the inertial frame of reference, but are expanded on or about the Body Axis System.

[a]Printout from the Time Histories Program

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2.6 CONFIGURATION CHANGE EFFECTS

The effects of configuration changes, such as planform, camber shape, structural elasticity, etc., can be evaluated by performing any of the above analyses for each configuration change.

2.7 EXTENDED FLEXSTAB CAPABILITIES

Present FLEXTAB capabilities can be extended through interfacing or linking with computer programs outside the FLEXSTAB system. An example is taking the loads or elastic deflections at the structural grid points calculated by FLEXSTAB and inputting them into the NASA structural analysis computer system, NASTRAN (ref. 6), to calculate internal structural stresses at specified flight conditions. All such interfaces involve special problems concerning data arrangement, which are the responsibility of the individual user.

3.0 SCOPE AND LIMITATIONS OF FLEXSTAB FORMULATIONS

The FLEXSTAB system is designed for static and dynamic stability evaluation. The system does a control-fixed dynamic analysis and is valid only for low frequencies, i.e., reduced frequencies much less than one. Frequencies involved in flutter and load alleviation studies are beyond the range of the FLEXSTAB formulation. The FLEXSTAB system is based on linear aerodynamic and structural theories incorporated into two sets of equations of motion. One set of equations describes steady reference trimmed flight. The second set describes unsteady perturbations relative to the steady reference flight condition. Both sets of equations can be nonlinear as a result of user-input empirical aerodynamic data or, in the case of the unsteady equations, as a result of strong perturbations.

Five fundamental coordinate systems are employed in the FLEXSTAB formulation: two inertial reference frames and three mean reference frames, the latter being used as body-fixed coordinate systems. The use of these fundamental coordinate systems allows each section or discipline in FLEXSTAB to be formulated in an efficient manner. Descriptions of geometric, structural, and aerodynamic properties and stability characteristics are made with respect to their most appropriate coordinate systems. Use of mean reference frames allows the equations of motion of a flexible aircraft to be identical in form to those of a rigid aircraft. This leads to two important features of the FLEXSTAB system: (1) a logical merger of quasi-steady and low-frequency dynamic aeroelasticity through the residual flexibility approximation; and (2) a consistent basis for incorporating empirical rigid aerodynamic data into the analysis.

3.1 CONFIGURATION

The FLEXSTAB system is designed to analyze configurations with multiple wings and bodies (i.e., wing-body-tail-nacelle-struts, etc.). The configuration representation is reduced to a collection of planar surfaces representing wings, tails, and struts, and bodies of revolution representing fuselage, nacelles, external stores, etc. Spatial relationships between the actual placement of aircraft components, such as the placement of the wing on the body and/or the horizontal stabilizer on the vertical fin, can be represented in the FLEXSTAB system. The system as currently formulated demands configuration symmetry about the X-Z plane.

The planar surfaces defining the wing, tail, etc., are subdivided into panels for the aerodynamic representation. Although there are some restrictions on the paneling of these surfaces, leading and trailing edge control surfaces can usually be modeled. The number of panels necessary to define these components is a function of the complexity of the geometry and the desired resolution of the analysis. Computer analysis cost is roughly proportional to the cube of the number of aerodynamic elements. These aerodynamic elements include the number of planar surface panels, body segments, and panels placed on interference bodies which account for the aerodynamic interference between wings, bodies, etc.

3.2 AERODYNAMICS

The aerodynamic representation used in the FLEXSTAB system is based on the finite element method described by Woodward (refs. 7 and 8) to solve the linearized potential flow equations for supersonic and subsonic speeds. Results may be used at transonic speeds, recognizing that the nonlinear terms of the transonic flow equation are neglected. An additional limitation on this aerodynamic method is that the flow is considered to be inviscid; strong shock wave effects are also neglected. The severity of these limitations is a function of the configuration and flight conditions. For configurations and flight conditions for which the flow remains attached, without strong shocks or separation, predicted aerodynamic characteristics generally agree well with the observed characteristics. For configurations dominated by strong viscous flow phenomena the FLEXSTAB system may still correctly predict many aerodynamic trends. Some capability exists within the FLEXSTAB system to correct empirically these aerodynamic deficiencies. These capabilities are discussed later in this section.

The unsteady aerodynamics are based on a low-frequency approximation that extends the basic steady aerodynamic method to the calculation of unsteady aerodynamic derivatives. The method includes the effects of an unsteady wake and the effects of the finite speeds of disturbance propagation. These effects are included only to a first order approximation, which is valid when the flow incidence varies slowly. Error is in the order of the square of the reduced frequency $(0(k^2))$; the frequency of a harmonic time dependence, ω, normalized with respect to the frequency with which an aircraft traverses the spatial distance, ℓ, between the point where a cause of unsteadiness is located and the point where its effect is significant to the problem (i.e., $k = \omega\ell/U$). For a wing alone undergoing pitch oscillations, ℓ is taken to be the mean wing chord. The low-frequency approximation is unique in that it has the same general, three-dimensional capability of the steady aerodynamic method at both supersonic and subsonic speeds—a feature not found in other unsteady formulations. The unsteady aerodynamic theory serves to predict aerodynamic damping and inertia associated with aircraft stability prediction.

3.3 STRUCTURES

Two modes of structual representation are available within the FLEXSTAB system. For high aspect ratio configurations, the structure may be described by beam theory using programs within the FLEXSTAB system. For more arbitrary configurations, the system will accept the output from most finite element structures programs such as NASTRAN or ATLAS (the latter is a Boeing structures program).

The internal structures programs represent the aircraft configuration as a collection of beams. Each component of the configuration (wings, body, etc.) has an elastic axis that is assumed to deform by bending and twisting. The elastic axes are divided into finite elements from which the flexibility matrix, the mass matrix, the free vibration mode shape matrices, and the transformation matrices required to formulate the structural equations of motion are derived. Experience has shown that the beam theory approximation (as used in the FLEXSTAB system) is sufficiently accurate for aeroelastic predictions if configuration bodies have slenderness ratios less than 0.15 and if wings have aspect ratios greater than 6.

One of the attractive features of FLEXSTAB is its ability to accept the output of most finite element structures programs. The configuration must be modeled such that body-like structures are reduced to one-dimensional line models and wing-like structures are reduced to two-dimensional planar models. The configuration is represented by a constrained flexibility matrix in terms of translational degrees of freedom. Accepted as input into the FLEXSTAB system are:

- A constrained flexibility matrix

- A mass distribution matrix

- Rigid body mode shape matrix

- Free vibration mode shape matrix

- Generalized mass matrix

- Generalized stiffness matrix

The first three matrices are required for a static elastic analysis. These matrices must be supplemented with the remaining three matrices for a residual-elastic dynamic analysis. Constrained flexibility matrices input into FLEXSTAB are transformed into free flexibility matrices that describe deformations relative to a mean axis system compatible with the free vibration mode shapes. A free flexibility matrix implicitly contains inertial effects.

In a dynamic stability analysis, FLEXSTAB uses the free vibration mode shape amplitudes as structural degrees of freedom. The low-frequency modes are included in the equations of motion by introducing their structural and aerodynamic inertial, damping, and stiffness forces. For those high-frequency modes that are included in the equations of motion, the inertial and damping forces related to their independent motions are neglected as small. However, the aerodynamic stiffness and the structural flexibility of the high-frequency modes are included, leading to quasi-static motions in the degrees of freedom. The structural flexibility of the high-frequency modes is computed as a residual flexibility. This operation generates the term governing the quasi-static participation of the high-frequency modes without even having computed their eigenvalues or mode shapes. A simplified dynamic analysis may also be performed neglecting residual flexibility and using the static-elastic formulation.

3.4 STABILITY ANALYSIS

The FLEXSTAB system will analyze steady or unsteady, longitudinal, and lateral directional motions. For steady analysis, the aircraft is defined within the system by its:

- Geometry

- Aerodynamic influence coefficient matrix

- Rigid body inertia properties

- The matrices listed in section 3.3 and the free flexibility matrix[1] of the unrestrained structure

The flight condition to be evaluated is input as Mach number[2] and altitude or dynamic pressure, angle of bank, pitch[3], yaw and roll rates, and either thrust or flightpath angle. The aircraft is balanced or trimmed by adjusting the appropriate control surfaces and either thrust or flightpath angle. Empirical aerodynamic data can be used in the trim calculations. An option also exists by which the user may specify the trim conditions.

Static stability derivatives and parameters listed in tables 3 and 4 are calculated following standard conventions as defined in references 1 and 5. The calculation of yaw rate and sideslip stability derivatives neglects products of sideslip and angle of attack, wing camber, etc., which can have a dominant effect when dihedral is small (ref. 9). The calculation of elastic stability parameters implicitly contains the effects of inertial relief inherent in the free flexibility matrix. In addition, FLEXSTAB computes the deformed structural shape, the structural loads, and the lifting surface pressure distributions.

For unsteady motion, the elastic aircraft structure may be treated as being static-elastic, in which none of the free vibration modes are included in the dynamic equations of motion or as residual-elastic, in which some of the free vibration modes are included. For the residual-elastic analysis FLEXSTAB uses the free flexibility matrix, the free vibration mode shapes, and their corresponding frequencies to compute a residual flexibility matrix. The aircraft's unsteady aerodynamic matrix is also necessary for either elastic or rigid analysis of unsteady aircraft motion.

The FLEXSTAB system calculates the dynamic stability derivatives and characteristics listed in tables 5, 6, and 7. If the equations of motion are linear, their characteristic equation is rooted to find the dynamic modes of motion, damped and undamped natural frequencies, and the degree of modal damping. If the equations of motion are nonlinear as a consequence of either nonlinear aerodynamic data or large perturbation motions, the dynamic stability is evaluated from time history plots generated by FLEXSTAB.

3.5 EMPIRICAL CORRECTIONS

The FLEXSTAB system has several options by which empirical aerodynamic data can be input to supplement or replace calculated data. The empirical aerodynamic data can be

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[1] FLEXSTAB computes this from the constrained flexibility matrix.
[2] Corresponding aerodynamic influence coefficient matrix must be used.
[3] Alternately, load factor can be specified rather than pitch rate.

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used in the determination of both static and dynamic stability characteristics and in the determination of the aircraft's trim parameters. Wind tunnel force data, input in tabular form, can be used to represent the aerodynamic characteristics of a configuration treated as a rigid body, which is then modified by the theoretically calculated elastic increments.

The theoretical aerodynamic solution can be modified in several ways. The elements of the aerodynamic matrix can be arbitrarily modified to better match experimental data. The boundary conditions can also be modified by user-defined external flow conditions. These conditions can consist of arbitrarily defined flows or downwash that vary over the configurations and can be a function of the trim parameters and flight motions. The calculated loads on the configuration can also be defined by specifying an external load or lifting pressure distribution, which can vary with angle of attack and sideslip. Changes in the aerodynamic solution will affect the elastic increments, loading, and deformations, as well as the stability parameters. These empirical correction methods can be quite successful for improving rigid aircraft analysis, but their value for improving flexible aircraft analysis has not been proven.

4.0 FLEXSTAB PROGRAMS

The FLEXSTAB system is arranged into 14 separate programs. These programs can be categorized into four major groups: (1) geometry definition, (2) aerodynamic modeling, (3) structural modeling, and (4) analysis. These programs can be linked by tape or disk data transfer and can be executed singularly or consecutively in a single run.

4.1 GEOMETRY DEFINITION GROUP

The geometry definition group consists of one program—the GEOMETRY DEFINITION (GD) PROGRAM. This program is used to define the configuration geometry for subsequent sections. Plotting capability is provided.

4.2 AERODYNAMICS MODELING GROUP

The aerodynamics modeling group consists of two programs—the AERODYNAMIC INFLUENCE COEFFICIENT (AIC) PROGRAM and the AIC MATRIX CORRECTION (CAIC) PROGRAM. The AIC program generates the various aerodynamic matrices necessary in the analysis section. The CAIC program is used to modify elements of the AIC matrix to improve the solution, if desired, by the user before being used in the analysis section.

4.3 STRUCTURAL MODELING GROUP

The structural modeling group consists of five programs. Four of the programs are used for beam theory modeling of the structure; the fifth, the EXTERNAL STRUCTURAL INFLUENCE COEFFICIENT (ESIC) PROGRAM, is used as an interface between finite element structural programs and the FLEXSTAB system. The internal beam theory programs consist of the INTERNAL STRUCTURAL INFLUENCE COEFFICIENT (ISIC) PROGRAM, the ELASTIC AXIS PLOT (EAPLOT) PROGRAM, the NORMAL MODES (NM) PROGRAM, and the NORMAL MODES PLOT (NMPLOT) PROGRAM. For structural modeling either the beam theory modeling or the external finite element method would be used, not both. For a rigid configuration, neither would be necessary.

The INTERNAL STRUCTURAL INFLUENCE COEFFICIENT (ISIC) PROGRAM uses beam theory to calculate the structural stiffness and flexibility matrices and mass and inertial properties. The user may use the ELASTIC AXIS (EAPLOT) PROGRAM to plot the configuration elastic axis, including the location of nodes, junction points, and lumped masses defined in the ISIC program. If residual elastic, the output data from ISIC is transferred to the NORMAL MODES (NM) PROGRAM to calculate the free vibration mode shapes and eigenvalues. The user may use the NORMAL MODES PLOT (NMPLOT) PROGRAM to plot the modal displacements and rotations of aerodynamic panel centroids relative to their static positions.

4.4 ANALYSIS GROUP

The analysis section is made up of six programs: the STABILITY DERIVATIVES AND STATIC STABILITY (SDSS) PROGRAM, the PRESSURE DISTRIBUTION PLOT (PDPLOT) PROGRAM, the TIME HISTORIES (TH) PROGRAM, the TIME HISTORIES PLOT (THPLOT) PROGRAM, the AERODYNAMIC LOADS (ALOADS) PROGRAM, and the STRUCTURAL LOADS (SLOADS) PROGRAM. The SDSS program is the heart of the analysis group, generating data for the other programs within the group. Geometric, aerodynamic, and structural definition data from the previous groups are transferred to SDSS, along with a definition of the flight conditions to be analyzed. SDSS trims the aircraft, calculates the static and dynamic stability derivatives and parameters, aerodynamic loading, and elastic deformation, and evaluates the stability and control characteristics of configurations governed by linear equations of motion.

If the equations of motion are nonlinear as a consequence of user supplying nonlinear aerodynamic data or wanting to investigate large perturbation motions, or if discrete gust disturbances are input, the TIME HISTORIES (TH) PROGRAM is used to evaluate dynamic stability. The THPLOT program can be used to plot the time response of the aircraft's position and velocities.

The PRESSURE DISTRIBUTION PLOT (PDPLOT) PROGRAM is used to plot the lifting pressure distribution on the configuration. The AERODYNAMIC LOADS (ALOADS) PROGRAM is used to integrate the steady symmetric airloads to calculate forces and moments such as shear, bending, and torsion on a specified region on the configuration. The program may also calculate elastic deflections at structural grid points when ESIC has been used to generate the structural matrices.

The STRUCTURAL LOADS PROGRAM (SLOADS) prints user-selected loads on the elastic axis calculated by the SDSS program. The user can request symmetric, antisymmetric, elastic, rigid, and perturbation loading due to the motion variables, control deflections, and vibration modes. The SLOADS program can be used only for cases in which ISIC was used to define the structural properties. All the load matrices used in ALOADS and SLOADS are generated in SDSS.

5.0 PROGRAM IMPLEMENTATION

The initial issuance of the FLEXSTAB system is designed to operate on Control Data Corporation's 6000 and 7000 series general-purpose computers. CDC 6000-series computers must have a minimum of 131 K word central memory. CDC 7000-series computers must have a minimum of 65 K word small memory and 512 K word large memory. The minimum configuration of either series must contain the following peripheral equipment:

- One card reader

- One printer

- One card punch

- One tape transport

- A disk system with at least a 2.5-million-word capacity for limited problem capability and a 12-million-word capacity for general problem capability.

Data to be plotted are processed by a CalComp off-line 30-in. drum plotting system consisting of a digital pen plotter model 763 operating under control of a model 780 tape transport unit.

FLEXSTAB is designed to run under control of the SCOPE 3 and KRONOS 2 operating systems on 6000-series computers or SCOPE 2 on 7000-series computers. The FORTRAN Extended compiler (Version 3.0 or 4.2) and the compass assembler (Version 3.0) are used by FLEXSTAB. CalComp basic software routines are required for the plotting programs. This software package is distributed by California Computer Products, Inc.

An IBM 360/370-0S version of the FLEXSTAB version is also being developed. The IBM version will require approximately 300 K bytes of central memory.

6.0 DOCUMENTATION

The documentation for FLEXSTAB is contained in four volumes: a theoretical manual, a user's manual, a program description manual, and a demonstration case manual. The contents of these manuals are described below.

6.1 VOLUME I—THEORETICAL MANUAL

The *Theoretical Manual* contains the detailed theoretical derivation of the formulation used for the structures, aerodynamic, static, and dynamic stability calculations in the FLEXSTAB system. This manual explains the assumptions and limitations inherent in the formulation and provides the background necessary to obtain maximum use of the FLEXSTAB system.

6.2 VOLUME II—USER'S MANUAL

The *User's Manual* describes how to operate the FLEXSTAB system and is the primary guide to preparing program input. The manual is divided into chapters that cover each of the programs. Program execution procedures, user input guidelines, job control card arrangement, and input formats are given for each program. Input decks are shown diagrammatically so that the order of the input cards will be clearly evident. Printed output from each program is listed, and timing and line-count estimates are provided. Supplementary information can be found in the appendixes and in volume III, the *Program Description*.

6.3 VOLUME III—PROGRAM DESCRIPTION

The objective of the *Program Description* is to provide a general understanding of the FLEXSTAB system and the interrelationships of its components. By itself, this manual presents a broad picture of the FLEXSTAB system, with information to thoroughly familiarize the reader in all aspects of its design and operation. In this sense, the manual is of value to the analyst as well as the programmer. When supplemented with the comment cards in the source listing, the manual provides a complete and detailed description of every routine in the FLEXSTAB system. Although most of the material presented in the manual is free of technical programming terms, it is assumed that the reader is familiar with Control Data Corporation's 6600 digital computer and the SCOPE 3.1 operating system.

The *Program Description* illustrates in sequence, via diagrams and flow charts, the important internal blocks of logic within each program of the FLEXSTAB system and the major areas where data is input to and output from each of the programs. In addition, the manual is a guide to program maintenance, updating, and modification.

6.4 VOLUME IV—DEMONSTRATION CASES AND RESULTS MANUAL

The *Demonstration Cases and Results Manual* discusses the test cases used to demonstrate the FLEXSTAB system. Included in the demonstration were the Boeing 707-320B, the Boeing B2707-300PT (SST), the Lockheed YF-12A, and two very simple program checkout models. Volume IV outlines and discusses the input data preparation and presents the results of these cases. The description of the input data preparation is designed to assist new users. When used in conjunction with volume II, the *User's Manual,* the two manuals provide an excellent guide for input data preparation.

7.0 USER EXPERIENCE

User experience with the FLEXSTAB system has been mainly confined to several organizations within The Boeing Company, and the Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base. Initial usage resulted in uncovering many errors typical of a system as large as FLEXSTAB. Recent user feedback has been more confined to dealing with future development than the uncovering of additional errors. With the number of users increasing, more analysis combinations will be exercised, undoubtedly uncovering more errors. It should be emphasized that all known errors have been corrected and that every major section of the system has been successfully executed.

Configurations analyzed within The Boeing Company have included the Boeing 707-320B, Boeing B2707-300PT (SST), Boeing B52E, and the Lockheed YF-12A. FLEXSTAB results have compared favorably with other theoretical methods and wind tunnel and flight test data. Details of these comparisons for the B52E and the YF-12A are given in references 10 and 11. Typical aerodynamic paneling of these configurations is shown in figures 2 through 5.
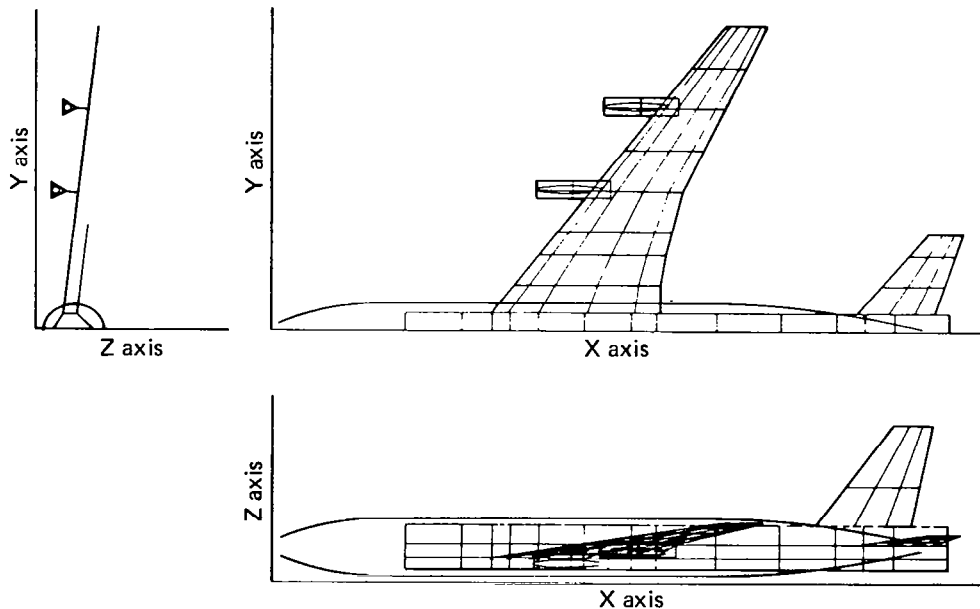

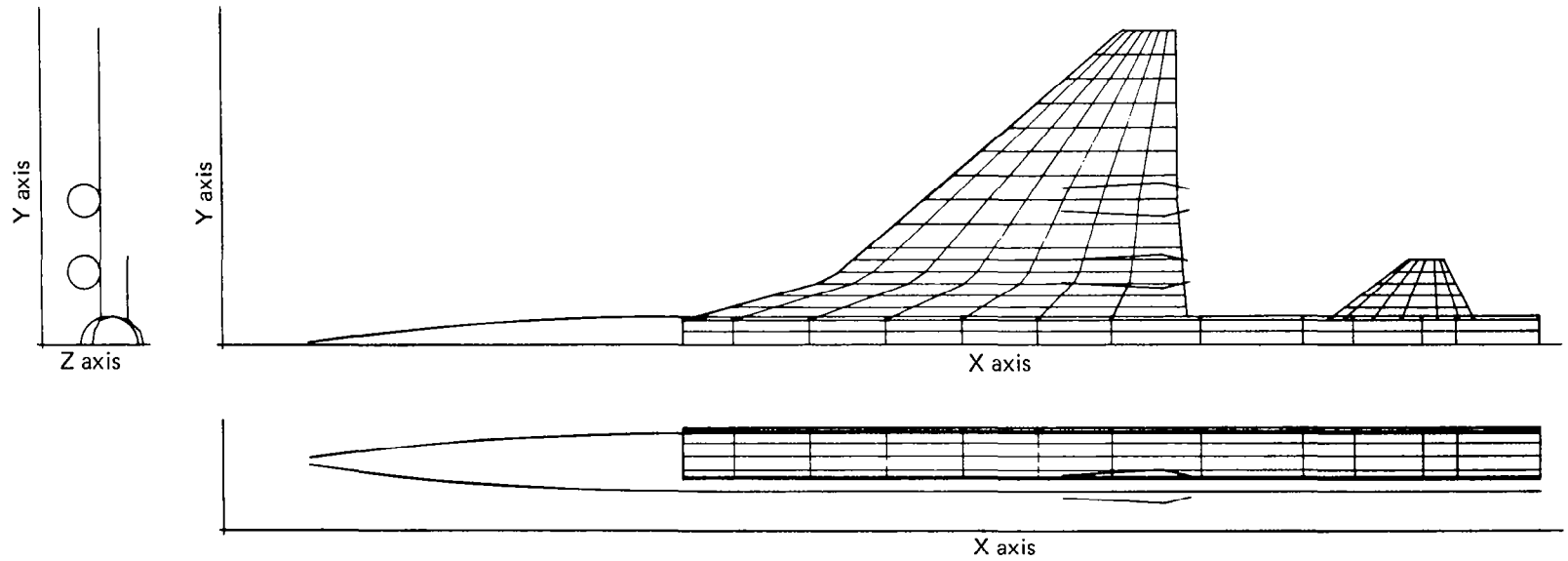FIGURE 2.—FLEXSTAB REPRESENTATION—BOEING 707-320B

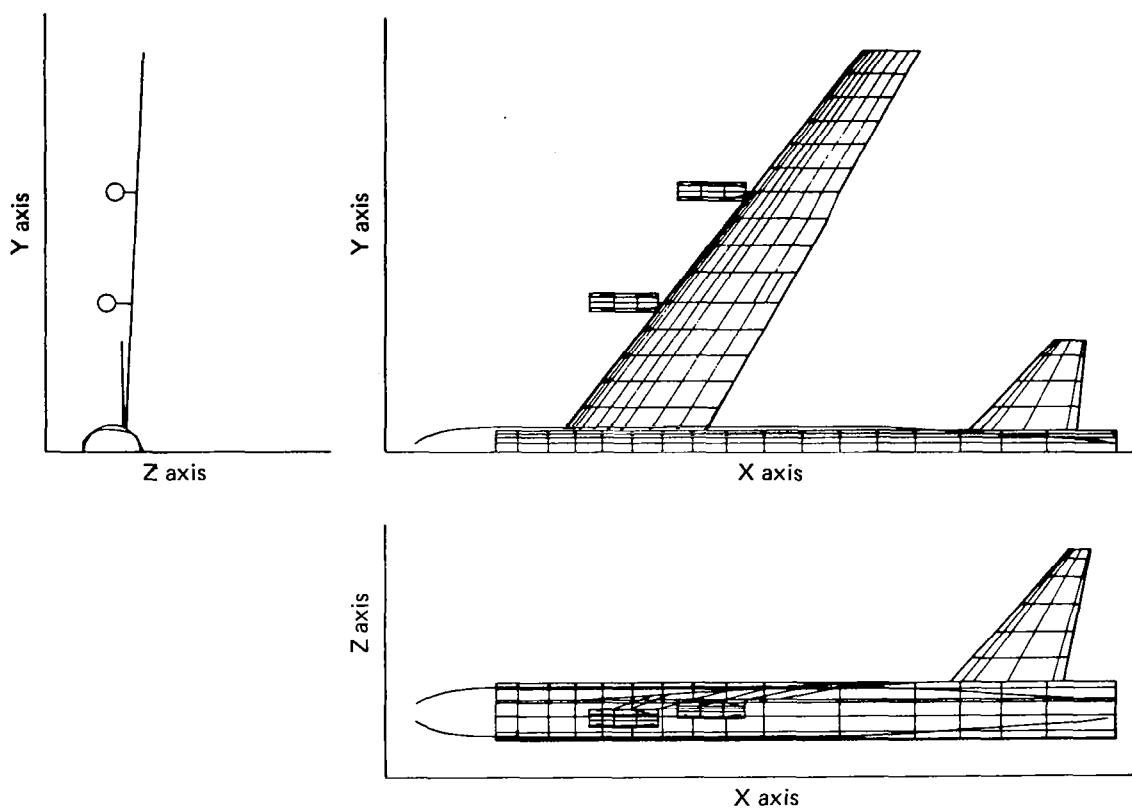FIGURE 3.—FLEXSTAB REPRESENTATION—BOEING B2707-300

FIGURE 4.—FLEXSTAB REPRESENTATION—BOEING B52E

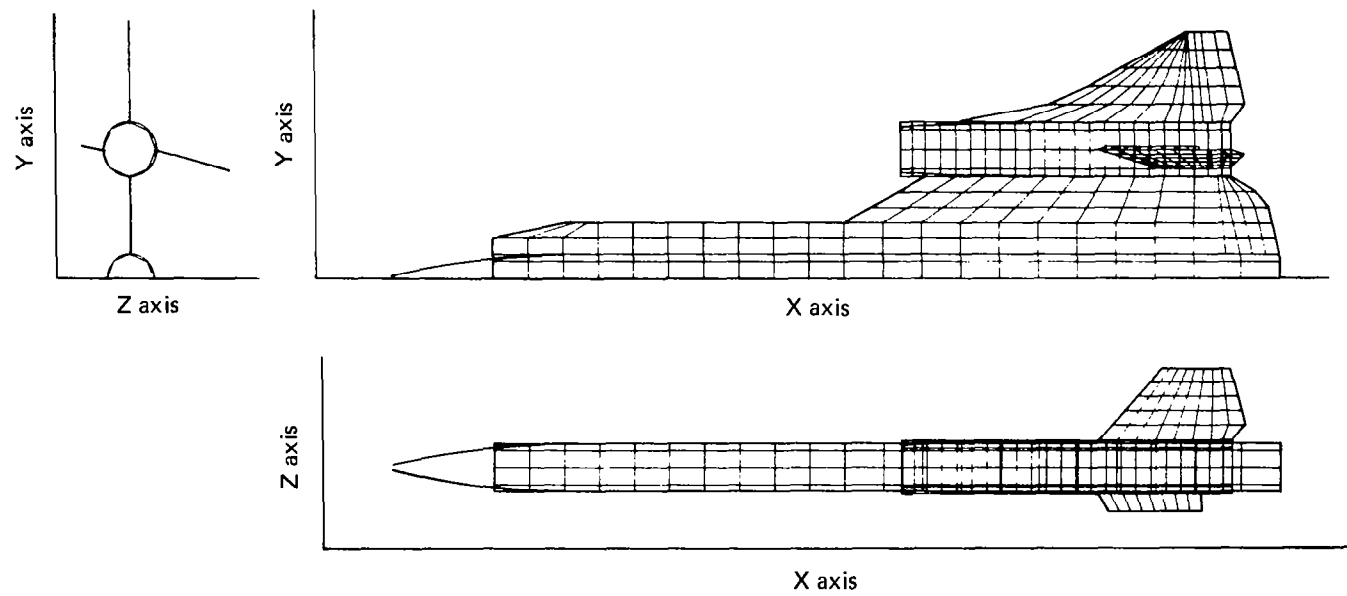Y axis

Z axis

Y axis

X axis

Z axis

X axis

FIGURE 5.—FLEXSTAB REPRESENTATION—LOCKHEED YF-12A

Some sample computer run times are shown in table 8 for different type analyses. Computer run times are dependent mainly on the number of aerodynamic and structural elements used to define a configuration and are also dependent on the analysis options within the various programs. CDC 6600 times shown in table 8 are for the Boeing Computer Services computer running on the KRONOS 2.0 operating system. CDC 7600 times are for the Lawrence Berkeley Laboratories of the University of California computer running on the SCOPE 1.0 operating system. Times may differ significantly on other installations.

TABLE 8.—SAMPLE RUN TIMES

Computer	CDC6600[a]				CDC7600[b]
No. of aerodynamic elements	130	224	367	576	576
No. of structural nodes		126	148	346	346
No. of eigenvalues		1			
Program	Time central processor unit, sec				
GD	20	42	55		
AIC longitudinal only	500		1600	3000	600
longitudinal and lateral		1400			
CAIC			50		
ISIC					
Static elastic		1700			
Residual elastic		2280			
NM		400			
ESIC			900	3000	600
SDSS Rigid	70	120	775	1000	125
Static elastic		1400	1700	2700	300
Residual elastic		2140			
TH		50-1500			
SLOADS		50			
ALOADS				100	15
NMPLOT } EAPLOT } PDPLOT } THPLOT }	10 to 30				

[a]Boeing Computer Services,
CDC6600, KRONOS 2.0 operating system

[b]Lawrence Berkeley Laboratories,
CDC7600, SCOPE 1.0 operating system

8.0 VERSION CONTROL

The FLEXSTAB source code provides for a version control procedure which makes visible all coding changes (e.g., changes due to error corrections, elimination of extraneous code, modifications stemming from engineering reformulation, revised numerical algorithms, etc.).

Basic to this arrangement is the assignment of a global LEVEL, RELEASE, and PATCH number to the program. In addition, each source statement in the code carries a unique number; the coding revisions required to correct any given error (a PATCH) can be traced by means of this system of numbers. When sufficient PATCHES have been accumulated to become cumbersome, they will be consolidated, and a new program RELEASE will be issued. New FLEXSTAB LEVELS will reflect material changes in capability, major improvements in algorithms, etc.

The first formal version of FLEXSTAB issued by NASA is designated LEVEL one, RELEASE two, PATCH zero, i.e., version 1.02.00. The program issuance is in the form of source code rather than in object form or absolute form. The NASA issuance also includes the input data and results for the demonstration cases described in reference 4.

Boeing Commercial Airplane Company
    P.O. Box 3707
        Seattle, Washington 98124, September 5, 1974

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GLOSSARY [4]

Aerodynamic centroid—geometric location of the center of aerodynamic pressure acting on an *aerodynamic segment* [5]

Aerodynamic derivatives—constants of proportionality between aerodynamic forces and small changes of aircraft *motion variables* from the value zero

Aerodynamic influence coefficients—coefficients in any linear aerodynamic relation, but used herein as the coefficients linearly relating lifting pressure coefficients to flow incidence

Aerodynamic panel—quadrilateral segment of an *aerodynamic mean surface,* the quadrilateral having two edges parallel to the free stream direction

Aerodynamic problem—a boundary value problem consisting of a flow equation and boundary conditions specified on the aerodynamic surface of an aircraft, on its wake surface, and at large distances from the aerodynamic surface

Aerodynamic segment—portion of a *thin* or *slender body* over which the strength of a distributed *flow singularity* is controlled by a single parameter, viz, an *aerodynamic panel* on thin and slender body *mean surfaces* and the segment of a slender body between two adjacent points on the slender body centerline

Body Axis System (X_B, Y_B, Z_B)—a right-handed, rectangular cartesian coordinate system constituting a *mean reference frame* and having its origin at the aircraft center of mass; the X_B, Z_B plane coincident with the aircraft plane of symmetry; and the X_B axis positive forward, into, and parallel to the free stream

Body-fixed axis system—a *mean reference frame*

Constrained flexibility matrix—the flexibility matrix for a kinematically constrained structure

Flow singularity—an elementary solution to the governing flow equations; simulates some flow phenomena

Free flexibility matrix—the flexibility matrix for a structure free of kinematic constraints (viz., such that sets of applied forces are in self-equilibrium)

Interference body—a shell placed around a "slender body" to account for interference and lift carryover effects.

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[4]A more complete glossary appears in reference 1.

[5]Italicized terms are also defined in the glossary.

Lateral-directional derivatives—"aerodynamic" and "stability derivatives" related to purely antisymmetric motion of an aircraft

Longitudinal derivatives—*aerodynamic* and *stability derivatives* related to purely symmetric motion of an aircraft

Low frequency approximation—an approximate theory of unsteady aerodynamics valid when the unsteadiness is a slow time variation, viz, unsteadiness characterized by *reduced frequencies* small by comparison with unity

Mass distribution matrix—see nodal mass matrix

Mean reference frame—a coordinate system translating and rotating with an elastically deforming aircraft in such a way that the momentum of the aircraft at any instant of time is equal to the momentum of a rigid aircraft translating and rotating with the coordinate system; also, a moving coordinate system relative to which the kinetic energy of the aircraft is a minimum; the *Reference, Body,* and *Stability Axis Systems* are mean reference frames

Mean surfaces—cylindrical or flat surfaces aligned with the undisturbed free stream where the *surface boundary conditions* are specified in a linear, first-order aerodynamic theory

Motion variables—a set of time-dependent variables which describe the motion of an aircraft relative to the Inertial Axis System, viz, the translation and rotation of the *mean reference frame* relative to the Inertial Axis System plus the elastic deformation motion relative to the mean reference frame

Nodal displacement components—in a finite element representation of a structure, the components of displacement at the *node points* which, when substituted into the displacement relations, describe the deformation at all points of the structure

Nodal force components—in a finite element representation of a structure, the components of force applied at the *node points*

Nodal mass matrix—matrix of inertially equivalent lumped masses, i.e., the matrix of mass quantities associated with the *node points* in a finite element structural representation, which, when multiplied onto time rates of change of *nodal displacement components,* describes the momentum of the structure

Node points—points where the applied forces and displacements are evaluated in the finite element representation of a structure

Pressure coefficient—the deviation of the local pressure from static free stream pressure normalized with respect to the dynamic pressure of the free stream

Quasi-steady maneuver—an unsteady maneuver in which the unsteadiness (i.e., the time rates of change of the translational and rotational velocities) is so small that time derivatives can be treated as negligibly small in the equations of motion

Reduced frequency—the frequency of a harmonic time dependence, ω, normalized with respect to the frequency with which an aircraft traverses the spatial distance, ℓ, between the point where a cause of unsteadiness is located and the point where its effect is significant to the problem, i.e., $k = \omega\ell/U$ where for a wing alone undergoing pitch oscillations ℓ is taken to be the *mean wing chord*

Reference Axis System (X, Y, Z)—a right-handed, rectangular cartesian coordinate system constituting a *mean reference frame* and having its origin located on the aircraft plane of symmetry, the X,Z plane coincident with the aircraft plane of symmetry, and the X axis positive aft aligned with the undisturbed free stream

Reference flight condition (state)—the steady, trimmed flight condition in which the static and dynamic stability of an aircraft is evaluated by the FLEXSTAB system

Residual elastic—see residual flexibility

Residual flexibility—the structural flexibility associated with free vibration mode shapes for which the generalized inertial and damping forces are neglected in the perturbation equations of motion

Rigid body mode shapes—displacement components, at points on an aircraft surface or at structural *node points,* arising from an infinitesimally small rigid body rotation and translation of an aircraft

Self-equilibrium—term referring to a system of forces having vanishing resultant forces and couples at any point, e.g., the system of aerodynamic, propulsion system, and inertial forces acting on an aircraft in free flight

Singularity strength—parameters controlling the strengths of *flow singularity* distributions on *aerodynamic segments*

Slender body—an aircraft configuration component having an aspect ratio equal in order of magnitude to its thickness ratio, e.g., fuselages, nacelles, pods, tip tanks, etc.

Stability Axis System (X_S, Y_S, Z_S)—a right-handed, rectangular cartesian coordinate system constituting a *mean reference frame* and having its origin located on the aircraft plane of symmetry, the X_S, Z_S plane coincident with the plane of symmetry, and the X_S axis positive forward aligned with the free stream in the *reference flight condition*

Stability derivatives—constants of proportionality between aerodynamic forces and small changes of aircraft *motion variables* from their values in the *reference flight condition*

Steady, reference flight condition—see *reference flight condition*

Structural nodes—see *node points*

Surface boundary condition—boundary condition on an *aerodynamic problem* requiring that the disturbed flow be tangent to the aerodynamic surface, neither penetrating it nor separating from it

Thin body—an aircraft configuration component having an aspect ratio at least an order of magnitude greater than its thickness ratio, e.g., wings, tail surfaces, struts, etc.

Trim parameters—all quantities appearing in the steady equations of motion which, for a particular aircraft, must have specified values in order for the equations of motion to be satisfied, i.e., velocity, rotation rate, control surface settings, bank angle, attitude, and thrust setting

Trim variables—six of the *trim parameters* that may be determined by solving the steady equations of motion treating these six parameters as unknowns

Trim solution—the values of the *trim variables* determined by solving the steady equations of motion

Wing-body problem—*aerodynamic problem* consisting of a wing-body combination used in the asymptotic expansion leading to the first-order approximate aerodynamic theory of the FLEXSTAB system